ARTICLE NO. 79-0980R

Thermal and Other Tests of Photovoltaic Modules Performed in Natural Sunlight

James W. Stultz*
Jet Propulsion Laboratory, Pasadena, Calif.

The nominal operating cell temperature (NOCT), an effective way to characterize the thermal performance of a photovoltaic module in natural sunlight, is developed. NOCT measurements for more than twenty different modules are presented. Changes in NOCT reflect changes in module design, residential roof mounting, and dirt accumulation. Other test results show that electrical performance is improved by cooling modules with water and by the use of a phase change wax. Electrical degradation resulting from the marriage of photovoltaic and solar water heating modules is demonstrated. The cost-effectiveness of each of these techniques is evaluated.

Introduction

THE electrical power output of photovoltaic solar cell modules is dependent upon the operating temperature of the cells, and for constant illumination, decreases at a rate of approximately 0.5%/°C with increasing cell temperature. Because of this temperature sensitivity, it is important to understand the thermal characteristics of modules so that modules can be designed to reduce cell temperature to the extent that it is cost-effective. An understanding of module operating temperature characteristics is also necessary to allow accurate prediction of module power output under field operating conditions, and to allow accurate comparison of the field electrical performance of different module designs.

The test and analysis activity described in this report was conducted between 1976 and 1978 as part of the engineering area of the low-cost solar array (LSA) project at the Jet Propulsion Laboratory (JPL). Understanding of the subject matter presented in this paper will be enhanced significantly by consulting Refs. 1 and 2, from which the material has been drawn. The major portion of the work has been the characterization of 29 modules according to their nominal operating cell temperature (NOCT) and determination of the effect on NOCT of changes in module design, various residential roof mounting configurations, and dirt accumulation.

Other tests, also thermal in nature, evaluated the improvement in electrical performance by cooling the modules with water and by channeling the waste heat into a phase change material (wax). Electrical degradation resulting from the natural marriage of photovoltaic and solar water heating modules was also demonstrated. The cost-effectiveness of each of these techniques is evaluated in light of the LSA cost goal of $0.50/W.

Photovoltaic Modules

The NOCT has been measured on all of the modules shown in Figs. 1-3. The block I modules (Fig. 1) were obtained in the first JPL procurement of off-the-shelf modules produced at the start of the LSA program. The block II modules (Fig. 2) are the first modules constructed according to JPL specification. Several modules (Fig. 3) have become available as an outgrowth of research and development tasks.

The module construction varies significantly. Basically, the solar cells are interconnected electrically and are contained by an encapsulant between a cover and a substrate.

Nominal Operating Cell Temperature (NOCT)

Figure 4 illustrates that modules of different designs operate at significantly different cell temperatures. Since module power decreases with increasing cell temperature at a rate of approximately 0.5%/°C, it is desirable to purchase solar modules by rating power at a cell temperature indicative of expected operating temperatures in the field. This approach provides greatly improved correlation between measured performance at rated conditions and expected

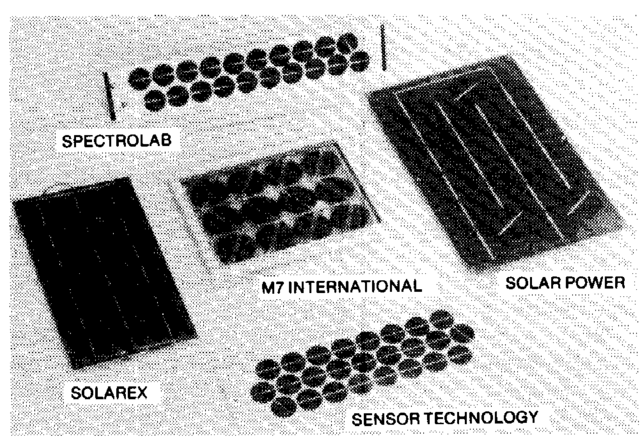


Fig. 1 Block I modules.

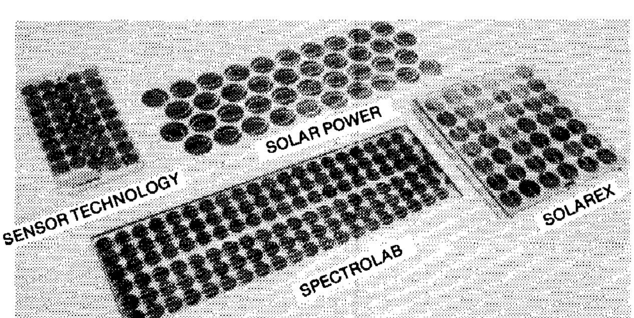


Fig. 2 Block II modules.

Presented as Paper 79-0980 at the AIAA Terrestrial Energy Systems Conference, Orlando, Fla., June 4-6, 1979; submitted July 10, 1979; revision received Oct. 25, 1979. Copyright © American Institute of Aeronautics and Astronautics, Inc., 1979. All rights reserved. Reprints of this article may be ordered from AIAA Special Publications, 1290 Avenue of the Americas, New York, N. Y. 10019. Order by Article No. at top of page. Member price $2.00 each; nonmember, $3.00 each. **Remittance must accompany order.**

Index categories: Photovoltaic Power; Solar Thermal Power.

*Member of the Technical Staff, Applied Mechanics Division. Member AIAA.

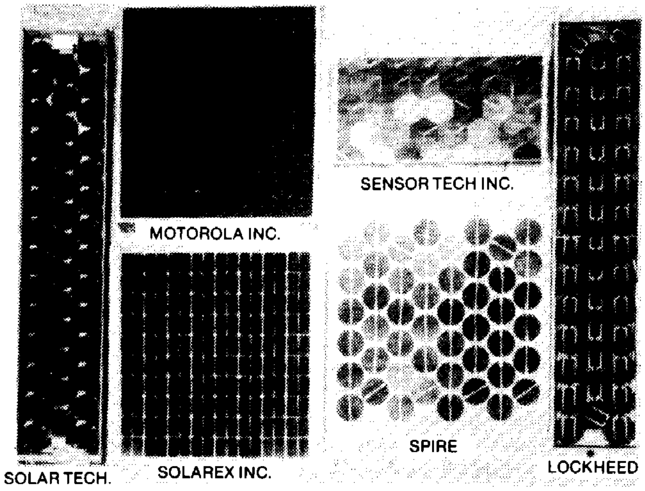


Fig. 3 Research and development modules.

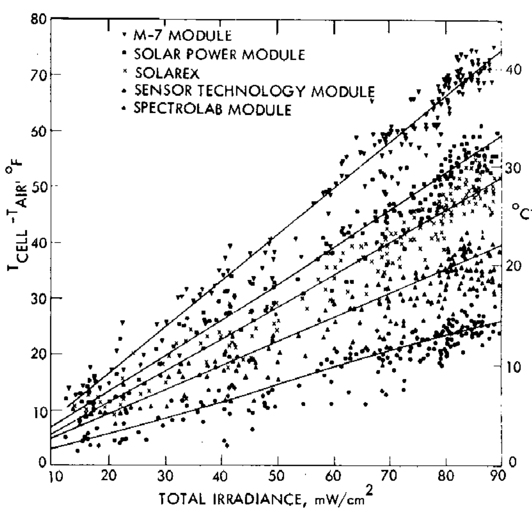


Fig. 4 ΔT vs insolation of the five module designs.

performance in the field. It also enables more accurate comparison of alternate module designs with different thermal properties and I-V/temperature characteristics, and should cause module-cell performance optimization to be more closely aligned with actual field operating conditions. Use of this approach is a necessary step toward standardization of module electrical performance parameters and manufacturer product interchangeability.

NOCT is determined experimentally in a nominal terrestrial environment (NTE), which is representative of the average environmental conditions in the United States during times when solar arrays are producing power. To define NTE, a study was conducted using computer analysis of weather tapes that describe the measured hour-by-hour variation in ambient temperature and insolation in nine representative geographic locations in the continental United States. For each 3-h interval, the following parameters were calculated:

1) Insolation incident on a solar panel tilted to the local latitude and faced south.

2) Solar cell temperature based on a) local air temperature, and b) thermal properties of a typical solar cell module.

3) Maximum power output of a solar cell module with typical I-V and temperature/intensity dependence characteristics.

Based on 10 years of weather data for each site, the values calculated for the above parameters were used to provide the average annual energy produced by a module at each combination of cell temperature and insolation level (on the tilted

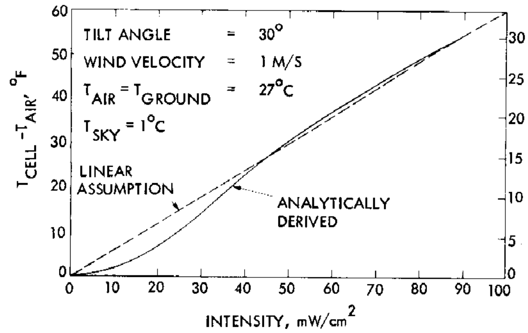


Fig. 5 Variation of ($T_{cell} - T_{air}$) vs insolation level for a typical solar cell module.

module). The results indicated that 50% of the energy from the assumed module is produced at insolation levels above and below about 80 mW/cm^2, and at cell temperatures above and below about 44°C. Using these values together with thermal properties of the assumed module, the properties of a median environment are calculated as: insolation = 80mW/cm^2; air temperature = 20°C.

Using this definition, 50% of array energy output is produced at environmental conditions less severe, and 50% at conditions more severe than those of the median environment. This environment represents a logical point for specifying module electrical performance, and hence has been adopted as the definition of the nominal terrestrial environment (NTE). The nominal operating cell temperature (NOCT) used for performance specification is measured cell temperature under NTE conditions, and, generally, will be different for each type of module. For the typical module used in the calculation procedure, the NOCT is 44°C.

Initial tests at JPL had suggested that the difference between cell and air temperatures ($T_{cell} - T_{air}$) was largely independent of air temperature and was essentially linearly proportional to the insolation level. It was felt that this relationship, if verified, could be used to interpolate accurately the NOCT temperature from cell temperature data obtained under the wide variety of ambient conditions present at various geographic locations at different times of year. To understand further the relationship between cell temperature and the environment, a number of small tests and analyses were conducted. One potential problem in using measured cell temperature data was the data scatter observed in the first test phase. This scatter was attributed to wind gusts, rapid ambient air temperature changes, and absolute magnitude of average air temperature. This scatter was reduced significantly by separating morning and afternoon data, and by adding solder to the thermocouple measuring the air temperature.

Another analysis was directed toward determining the proper way to average, or draw a line through, the measured data. The results of a simple analysis—using a computer model approximating the Solarex configuration—are shown in Fig. 5. This analysis illustrates that fitting the data with a straight line which passes through the origin is especially applicable for intensities greater than 40 mW/cm^2.

Using the same computer model, the sensitivity of cell temperature to tilt angles between 10 and 60 deg was investigated. In modules whose front and back surfaces are at approximately the same temperature, the total (sum of the front and back surfaces) heat transfer by radiation does not vary with tilt angle. For the same tilt angle range and an average wind velocity of 1 m/s, the total convective heat-transfer coefficient varied by ±4% about the peak value, which occurred at a 45-deg tilt angle. However, the analysis indicates that this is less than a ±1.5°C effect for the same heat input. Although initially this last result may seem questionable, an average module operating at the NOCT rejects almost twice as much heat by radiation as it does by

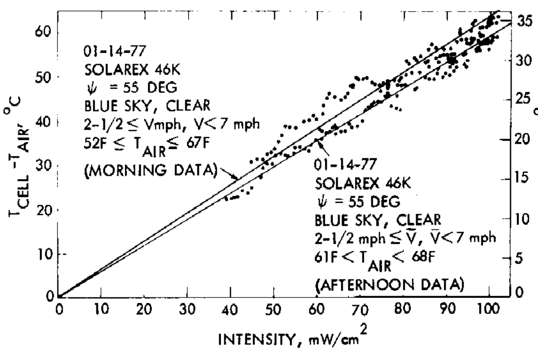


Fig. 6 Morning and afternoon ΔT vs insolation for the Solarex module.

convection. The two heat rejection paths are parallel. If the heat is maintained the same, in changing the tilt angle, the heat rejected is the same and divided between the two parallel paths. Since radiation is a fourth-power temperature function and is the predominant mode of heat rejection, a lesser change in module temperature is necessary to maintain a constant heat output. The conclusion of this anslysis is that neither radiation nor convection are strong functions of tilt angle.

From these analyses and tests it was determined that NOCT could be accurately interpolated from measurements made under widely varying test conditions. For standardization purposes the following test envelope (center is NTE) is proposed:

Mounting:	Tilted, open back, open circuit
Solar insolation:	80 ± 40 mW/cm^2
Wind velocity:	1 ± 0.75 m/s
Wind gust:	Less than 4 m/s
Air temperature:	20 ± 15°C

The procedure for determining NOCT calls for plotting $(T_{cell} - T_{air})$ against the insolation level as shown in Fig. 6 for a one- or two-day period when wind conditions are favorable. The NOCT value is then determined by adding $T_{air} = 20$°C to the value of $(T_{cell} - T_{air})$ interpolated for the NTE insolation level of 80 mW/cm^2. Fine adjustments are then made to account for off-wind conditions and extreme air temperatures using the correction factors (Fig. 7) calculated for modules without cooling fins, with back side open to the air, and with good solar and infrared optical properties, as is typical of current LSA modules. If these correction factors were not applied, a ± 3°C uncertainty in NOCT would exist.

Table 1 summarizes the tests used to substantiate the validity of the JPL test procedure. NOCT tests were completed on a separate set of block III modules at JPL and at

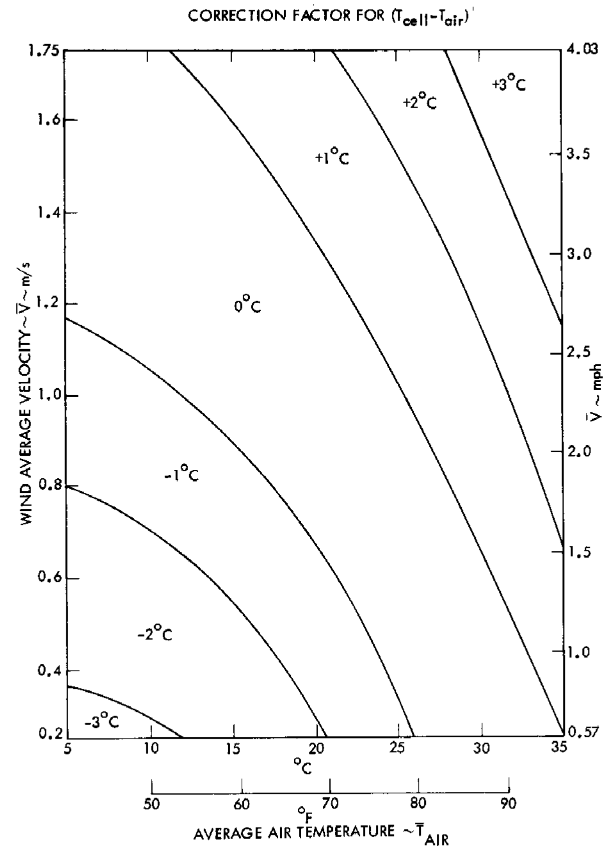


Fig. 7 Correction factor for $(T_{cell} - T_{air})$.

the Lewis Research Center.[3] Table 2 compares the results of these tests. From these results it is estimated that NOCT can be determined to within ± 1.5°C.

NOCT Test Results

Information regarding NOCT testing of the modules is summarized in Table 3. The table includes a material summary of each module, the number of tests made to determine NOCT (NOCT procedure requires a minimum of two), and a tabulation of thermally significant characteristics. A study of Table 3 enables some basic conclusions to be drawn about the module thermal design.

Air Voids

Air voids within a module should be eliminated. This conclusion was reached by analysis in the first thermal study[1];

Table 1 Thermal performance test summary

						Solarex 46 k			Spectrolab 130 k		
Test no.	Date	Tilt angle deg	Morning (M) or afternoon (A)	$\bar{T}_{air}$, °F	$\bar{V}$, mph	T_{cell} - T_{air}, °C	Correction factor °C	NOCT, °C	T_{cell}- T_{air}, °C	Correction factor, °C	NOCT, °C
1	11-01-76	45	M	90	2-3	25.5	+2	47.5	NA	NA	NA
2	11-18-76	55	M	77	1-2	27.8	0	47.8	21.9	0	41.9
3	11-18-76	55	A	80	1-2	26.1	0	46.1	20.2	0	40.2
4	01-11-77	55	M	63	2-3	28.8	0	48.8	22.0	0	42.0
5	01-13-77	55	M	56	3-4	28.8	0	48.8	22.1	0	42.1
6	01-13-77	55	A	64	3-4	26.4	+1	47.4	20.3	+1	41.3
7	01-14-77	55	M	60	1½-2½	28.5	−1	47.5	21.3	−1	40.3
8	01-14-77	55	A	65	1½-2½	26.5	0	46.5	20.5	0	40.5
9	01-17-77	55	M	70	1-2	27.9	0	47.9	21.2	0	41.2
10	01-17-77	55	A	80	1-2	26.5	0	46.5	20.3	0	40.3
						Average NOCT		47.5			41.1

Table 2 LeRC and JPL NOCT test summary

Block II module	NOCT, °C	
	LeRC	JPL
Solarex	46.0	47.1
Solar power	45.0	46.0
Spectrolab	41.0	41.1
Sensor technology	40.5	42.9

modules 5, 14, 19, and 20 experimentally illustrate the higher temperatures due to air voids. Module 5, which has an air void between the front cover and the cell, has the highest NOCT measured (59.6°C). Module 14 has only a partial void beneath the cell and the metal substrate, and a significant part of the cell is mounted directly above the metal substrate. As a result, the void in this instance is not a dominating thermal effect. Elimination of the void by injecting RTG 615 reduced its NOCT only from 46.3°C to 45.6°C.

The air void in modules 19 and 20 are not totally enclosed. In each case the void is created by a box, open at both ends, which is the support structure and/or a combination of support and substrate. Except for the box, module 20 is thermally very similar to module 15. Module 15 (no box) is 11°C cooler than module 20, giving an indication of the improvement in operating temperature that could be obtained with a total open configuration. (An 11°C reduction in module temperature translates into a 5% improvement in power.)

If the void thickness is greater than approximately 1.2 cm, heat transfer across the void by free convection is probable. If free convection is occurring, filling the void with RTG will not reduce the temperature as much as would occur if conduction through the air were the main heat transfer mode. To illustrate, the large void in module 5 was filled with RTG 615, which has a thermal conductivity 6.5 times that of air. The decrease in NOCT was only 5°C, from 59.6°C to 54.1°C. If conduction through the air had been the main mode of heat transfer, a reduction in NOCT of 10°C to 15°C would have been expected, since after filling, the module is just a thicker version of module 6, whose NOCT is 41.1°C. Air voids should be eliminated through module design. Filling the void as an afterthought will probably not be cost-effective.

Fins

Both modules 1 and 2 have a finned metal substrate and have the lowest NOCTs. The fins were machined from module 2 and the NOCT increased 2.7°C to 41.5°C. (This NOCT is not very different from that of module 8 which is thermally similar to module 2 but has no fins.) Therefore, the fins probably increased the power 1-2% (0.5%/°C).

Table 3 NOCT summary

No.	Module	Cover material	Encapsulant	Electrical isolator	Substrate: Material	Substrate: Geometry	Front intercell area color	NOCT, °C	No. tests performed	Thermally significant: Air Void	Metal substrate	Fins	Non metal substrate: Opaque	Trans.
	Block I													
1	Spectrolab	Glass	Sylgard	Dextilos paper	Aluminum	I-Beam	Aluminum	35.2	13		X	X		
2	Sensor Tech	Sylgard	Sylgard	Sylgard	Aluminum	Finned	Aluminum	39.0	6		X	X		
3	Solarex	Sylgard	Sylgard	Not required	G-10 board	Sheet	Green	47.5	10				X	
4	Solar power	Sylgard	Sylgard	Not required	G-10 board	Sheet	Green	48.8	5				X	
5	M-7	Plexiglas	Air	Not required	Plexiglas	Sheet	Transparent	59.6	5	X				X
	Block II and Mini													
6	Spectrolab	Glass	PVB	Not required	Polyester	Sheet	Transparent	41.1	9					X
7	Mini	Glass	PVB	Not required	Polyester	Sheet	Transparent	(43.1)	5					X
8	Sensor Tech	RTV 615	RTV 615	PVC/fiberglas	Aluminum	Pan	Aluminum	42.9	8		X			
9	Mini	RTV 615	RTV 615	PVC/fiberglas	Aluminum	Pan	Aluminum	(44.4)	13		X			
10	Solarex	RTV	RTV	Not required	Polyester	Sheet	Tan	47.1	8				X	
11	Mini	RTV	RTV	Not required	Polyester	Sheet	Tan	(46.2)	12				X	
12	Solar power	Silicone coating	RTV	Not required	Polyester	Molded	White	46.0	2				X	
13	Mini	Silicone coating	RTV	Not required	Polyester	Molded	White	(44.9)	12				X	
	Research and development													
14	EOS (Xerox)	Glass	RTV 615	Circuit board	Aluminum	Extruded	Blue	46.3	7	X	X			
15	Lockheed	Glass	Sylgard	Not required	Silicone coating	Sheet	Transparent	42.4	13					X
16	Motorola	Glass	Silicone gel	Polymid/glass	Stainless	Pan	Orange	53.3	10		X			
17	Sensor Tech High	RTV 615	RTV 615	RTV 615	Aluminum	Pan	Aluminum	44.5	15		X			
18	OCLI	Glass	RTV	Mylar	Aluminum	Sheet	Aluminum	45.5	5		X			
19	Solar Tech Int.	Glass	Neoprene	Neoprene	Aluminum	Box	Gray	51.3	5	X	X			
20	Arco Solar Inc.	Glass	PVB	Not required	Mylar	Sheet	Transparent	54.9	7	X				X
21	Solarex (Blk III)	RTV	RTV	Not required	Polyester	Sheet	Tan	46.5	15				X	
	JPL modified													
22	Solarex I (No. 3)	Sylgard	Sylgard	Not required	"Flake"/ G-10 board	Sheet	Green	55.1	10				X	
23	Solar Power I (No. 4)	Sylgard	Sylgard	G-10 board	Aluminum	Sheet	Green	50.6	8		X			
24	Sensor Tech I	Sylgard	Sylgard	Sylgard	Aluminum	"Sheet"	Aluminum	41.7	3		X			
25	EOS (Xerox) (No. 14)	Glass	RTV 615	Circuit board	Aluminum	"Voidless" extruded	Blue	45.6	4		X			
26	M-7 (No. 5)	Plexiglas	RTV 615	Not required	Plexiglas	Sheet	Transparent	54.1	6					X
27	M-7 (No. 26)	Plexiglas	RTV 615	Not required	"Painted" plexiglas	Sheet	White	57.2	10				X	
28	Spectrolab mini (No. 7)	Glass	PVB	Not required	Painted polyester	Sheet	White	44.6	8				X	
29	Solar Power I (No. 23)	Sylgard	Sylgard	G-10 board	Aluminum	Sheet	Green	49.6	10		X		X	

The average cost of the block I modules was approximately \$20/W. Module 2 has an output of about 5 W. Therefore, the fins contributed 0.1 W to this total. To be cost-effective, the fins would have to cost less than \$2 per module (20×0.1), which is possibly cost-effective for the block I modules, but obviously not at the 1986 cost goal of \$0.50/W. Since the block I purchase, there has been only one module design with fins, which is probably the best indication that fins may not be cost-effective even at today's prices.

Transparent vs Opaque Substrates

Modules 6, 7, and 15 have transparent substrates, and their NOCTs are about the same as those of thermally equivalent modules (modules 8 and 9) with metal substrates (no fins). In the first study[1] it was cautioned that the transparent module in a residential roof installation would run warmer due to heating of the air void (very similar to that of module 20) created between the roof and the module.

Tests at JPL and by General Electric have demonstrated that a white reflective intercell area significantly increases the power output of the module. A diffuse white paint on the back of module 7 increased the power output by 8% and increased the NOCT by 1.5°C, from 43.1°C to 44.6°C.

Therefore, the net power increase is at least 7%. This is another reason for not using a transparent substrate. White polyester is used to create a reflective intercell area in modules 12 and 13. The use of white tedlar or porcelain has also been suggested as a means of obtaining the solar reflective finish. Although thermal performance is negligibly different using a white substrate rather than a transparent substrate, the demonstrated increase in electrical performance makes the white substrate the preferred design.

Metal vs Nonmetal Substrates

Depending upon the nonmetal material used, the thermal advantage of the metal substrate can be reduced to a negligible consideration. A comparison of the NOCT for modules 8, 9, and 18 (metal substrate) with modules 12 and 13 (white polyester) illustrates that the metal substrate (aluminum) is at most 3°C cooler. Moreover, after painting the back of module 7 (PVB substrate), the NOCT was only 0.2°C warmer than that of module 9. Also, bonding (Eccobond 57C) a 0.05-cm (⅛ in.) aluminum sheet (white exterior) to the back of module 4 (G10 board substrate) increased the NOCT from 48.8°C to 49.6°C. None of these differences is significant enough to make the metal substrate thermally preferred over a nonmetal substrate. If, as predicted, material cost favors less thermally conductive steel over aluminum, the thermal rating of the module with nonmetal substrate could be the same to slightly better than that of the module with steel substrate.

High-Efficiency Modules

The use of inexpensive rectangular cells will result in high-efficiency modules. The effect on NOCT of increasing the nesting efficiency from approximately 75% (circular cells) to 100% (square, rectangular, hexagonal) is obtained by comparing the NOCT of modules 8 and 17. The construction is essentially identical, except that module 8 uses circular cells and module 17 uses hexagonal cells to obtain the high nesting efficiency. A 1.6°C increase in NOCT, or less than a 1% decrease in power, is indicated with elimination of most of the noncell area.

Residential Roof Installations

A 1.22×1.22 m segment of a photovoltaic residential roof installation was simulated. The array consisted of three identical modules, and the NOCT of the center module (module 12) was determined. Initially, the mounting technique approximated that proposed by Lincoln Laboratory for residential demonstration purposes. In the Lincoln Laboratory configuration, the modules are suspended about 7.6 cm from the roof by supports that attach at the top and bottom edges of the module. Airflow beneath the modules is discouraged by this design, and only the modules mounted along the east and west edges will benefit from sporadic wind-induced air movement beneath the modules. Later, the attachment technique was changed to simulate hard mounting to the roof in order to thermally approximate a shingle module configuration.

With no airflow beneath the modules, as would be typical of the innermost-mounted modules, the NOCT is 9.5°C warmer (55.5°C compared to 46.0°C) than the NOCT for the same module mounted in the normal field installation. Modules along the east or west edge would be 3.9°C warmer, because some airflow is possible through the open sides. If the modules were attached along the side rather than along the top and bottom edges, the module would be 4.8°C warmer. A module suspended from the roof by legs rather than rails would be 3.4°C warmer.

This test series illustrates that higher operating temperatures will occur for residential roof installations, and the decrease in electrical performance will be 2-5% in the worst case. A mounting technique permitting more airflow could cut this penalty in half. However, the module support structure is also utilized to support ladders (or the equivalent), which enable the initial installation of the modules as well as future servicing to be carried out with no damage to the modules or the existing roof. A mounting technique which assures this protection is well worth a 1-2.5% decrease in electrical performance.

Hard mounting the module to the roof further increases the NOCT. For an uninsulated roof, the NOCT is 12°C (58.0°C compared to 46°C) warmer than the normal open-back field installation. If the roof is insulated on the attic side, the NOCT is 15.5°C warmer (61.5°C). Hard mounting this module creates an air void between the substrate and the roof. A shingle module should not and probably would not be designed in this manner. It is estimated that the temperature increase would be 4°C less if there were no air void. This estimate is based upon bonding "flake board" (1.9-cm thick) to the back of module 3; the NOCT increased 7.6°C (47.5°C to 55.1°C). Without the voids, the temperature rise would be similar to that of a module located in the center of the roof for the Lincoln Laboratory configuration.

Unless the module is suspended from the roof so that air can flow in all directions beneath the module, it may be better to hard mount the module, trading the slight decrease in performance for the saving in structure cost. Moreover, the module that is integrated into the roof installation may be better adapted for repair in the event of a leak. Repairing a leak located beneath a module mounted off the roof is not likely to be attempted by the average homeowner, and the repair could prove to be involved and expensive. In summary, the improvement in thermal performance of modules mounted in this manner (off the roof) may not justify the additional initial and long-term cost.

Dirty Modules

Measurements for modules with nonglass surfaces were made at tilt angle of 13 deg during June and July. Tilt angles of the glass-surface modules began at 13 deg and were at 18 deg by the end of the test period at the middle of August. These low tilt angles encourage maximum dirt accumulation with respect to specific test site. The NOCT for modules with nonglass front surfaces increased 1.3-2.2°C during the first week and remained constant during the next three weeks. The NOCT of modules with glass front surfaces increased less than 0.5°C during the three week period of dirt accumulation. Although greater for nonglass than for glass surfaces, the effect of dirt accumulation on NOCT is not significant.

Because of the effect of dirt accumulation on electrical output as well as on maintenance costs, ease of cleaning is a factor which may be of some significance. In routine cleaning of modules prior to the standard NOCT test, it has been observed that it takes more water, more towels, and more "elbow grease" to clean the nonglass front surfaces. The cleaning cost may therefore be significantly higher for nonglass than for glass front modules.

Operating Modules

NOCT is determined with a zero power output (open circuit conditions) to reduce the complexity of the test. Performance of a test during which maximum power was continuously removed from the module resulted in a reduction in NOCT of 2.9°C. This reduction offsets the temperature rise due to dirt accumulation—an effect which is not accounted for in the determination of NOCT.

Solar Dome Modules

Two solar dome concepts are being studied by Boeing. The weathered polyester film dome encloses the arrays and thereby eliminates the requirement for weatherproof encapsulation of the cells, screens UV, and enables a low-cost array structure. The resulting cost saving must be balanced against the significant reduction in power due to the high operating temperatures characteristic of the greenhouse.

Tests were made to evaluate the NOCT of a module in a solar dome. A Spectrolab block II module was used for the measurements, and the polyester film is identical to that proposed by Boeing. The procedure was carried out first with white and later with black flooring. The first set of data was obtained with the plywood floor painted white; the black floor was created using a layer of black plastic. The dome environment increases the NOCT of the module (normally 41.1°C) 28.2°C and 37.1°C for the white floor and black floor, respectively. A corresponding power reduction of 14.1% and 18.6% would be expected. The white paint also reflects more energy onto the cells; therefore, the improvement in performance is actually greater than 4.5%, as indicated by the NOCT difference. In a real application, the module should be positioned back (north) in the cylindrical enclosure as much as possible to maximize the reflective floor area in front of the module.

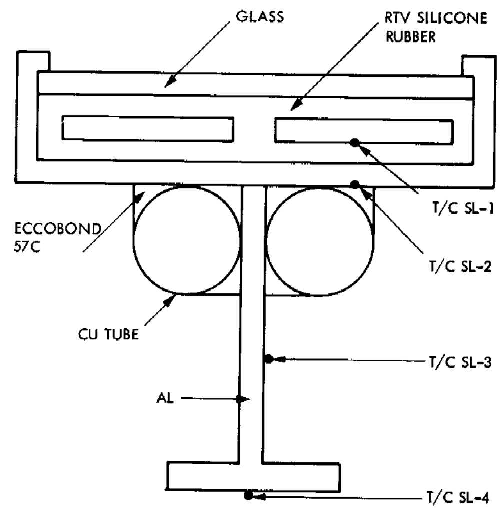
As Boeing has found, an active cooling system for a power station configuration is not economically feasible. However, the light weight of this system makes it well suited for roof installations (apartments, factories, etc.), and the high temperatures suggest the combination of photovoltaic with space and/or hot water heating. Toegether the two systems could prove to be economically viable.

Other Test Results

Water-Cooled Modules

This study was prompted because some applications involve the movement of a large amount of water. For example, the irrigation project in Nebraska pumps 60,000 gal/h or 1542/gal/ft^2 of module area. While this flow rate is adequate, much larger flow rates are possible with a simple gravity feed configuration, such as a common trough feeding water into the top of tubes attached or built into the back of the modules, and discharging it into a holding pond or into the supply system. A larger flow rate would improve the performance slightly.

In the test setup, water was circulated through two copper tubes bonded to the backside of a block I Spectrolab module. This module has two rows of cells mounted in a staggered pattern on an aluminum I-beam. As illustrated in Fig. 8, the copper tubes were bonded on either side of the I-beam beneath the cells with a thermally conductive adhesive (Eccobond 57C). The inlet water temperature was maintained constant during the test. Maximum power was continuously drawn from the module. Figure 8 also presents temperatures



MODULE TEMPERATURES~°C

THERMO COUPLE	IN AIR	H_2O INLET WATER TEMP 32°C	23°C	15°C
SL-1	47.8	38.9	32.8	25.0
SL-2	46.1	37.2	31.1	23.3
SL-3	43.3	35.0	29.4	21.7
SL-4	41.7	34.4	29.4	22.8

Fig. 8 Module temperature profile at noon (insolation = 95 ± 2 mW/cm²).

of the module as measured at noon. With water cooling, the gradient through the module is cut almost in half, and the cell is about 3°C warmer than the local water temperature. Reversing the flow (bottom to top) had no effect on the temperature profile, and there was no measurable change in $P_{\max}$ when the flow was increased by a factor of five.

The average electrical efficiency of the module (η_ϵ) was determined by:

$$\eta_\epsilon = \int P_{\max} \,\mathrm{d}\theta \Big/ \int LA \,\mathrm{d}\theta$$

where θ is the time, L is the total intensity, A is the module area, and $P_{\max}$ is the maximum power.

The η_ϵ values for the tests are presented in Fig. 9. Also shown is the η_ϵ without water cooling and the expected η_ϵ for other air temperatures assuming the calculated change in η_ϵ of 0.038%/°C change in average air temperature. On a hot summer day (35°C average air temperature), η_ϵ would be about 5.2% for the normal field installation with air cooling only. With 23°C and 15°C (75°F and 60°F) water, power generation on this same hot day could be increased 16.0% (η_ϵ – 6.03%) and 20.8% (η_ϵ – 6.28%), respectively. Even with 32.2°C (90°F) water, power generation would improve 11.0% (5.77% compared to 5.2%) on the summer-type day.

If it is not already available, pumping power will consume most or all of the improvement in power production. Therefore, while each application must be treated separately, cooling with water is not expected to be cost effective unless the application already involves the pumping of water or a gravity water feed system is possible. Assuming either of the latter conditions exists, the one-time plumbing cost will not be a significant cost factor; the cost of a module should not be increased significantly by building into the module substrate the cooling channels or the provision for bonding/inserting copper cooling tubes, which could be optional.

Combined Photovoltaic and Solar Water Heating Module

Absorber area requirements for heating water or some other fluid for home space and hot water heating are very large. For example, the solar absorber area required locally

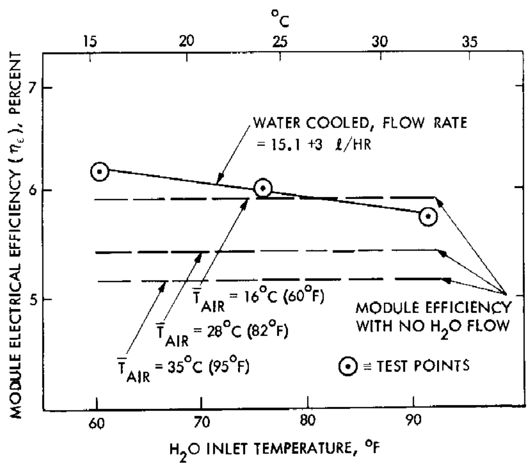


Fig. 9 Electrical efficiency of a water-cooled flat-plate photovoltaic module.

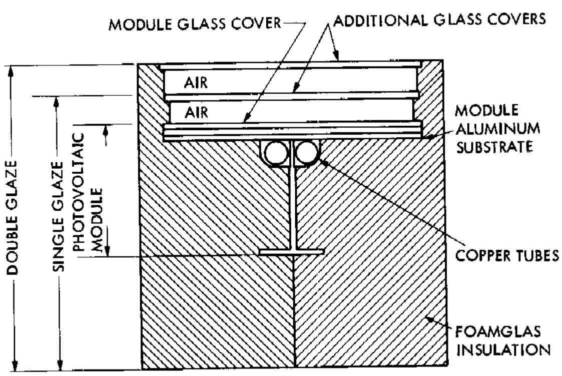


Fig. 10 Combined module configuration.

for an average home is 37.2 m^2 (400 ft^2).[4] This same home in the high desert of California requires 69.7 m^2 (750 ft^2) of absorber area. Solar House I at Fort Collins, Colo., uses all the roof area facing south (71.3 m^2) as solar collector area.[5] There will be many localities in which sufficient southfacing residential roof space is not available for both photovoltaic and solar heating modules.

Since solar cells have a solar absorbance as good as the average black absorber, the cells can replace the black coating of the solar water heater without significantly affecting its heating characteristics. However, electrical performance is significantly degraded by the one or two glass layers covering the absorber plate to minimize the front thermal losses. Tests were performed to evaluate the reduction in electrical efficiency that results from the marriage of a photovoltaic and solar heating module. Figure 10 illustrates the combined module. The Spectrolab block I module, used previously for water cooling tests, was surrounded on the back side by 7.6 cm of Foamglas insulation. The Foamglas is an excellent insulator and has structural characteristics allowing it to be machined to the desired configuration. Double strength window glass 0.32-cm thick was used for the glazing. Separation distance between the glass and the photovoltaic module (single glass configuration) was 1.27 cm.

The module was mounted in an east-west direction to minimize shadowing of the cells. The active side of the module was normal to the sun at solar noon. Water flow was from east to west at 15.1 ± 3 liters/h. This flow rate corresponds to 4.5 gal/ft^2 of absorber area and is about three times that commonly used in solar water collectors. The test flow rate was the lower practical limit for the circulation equipment and minimized the electrical mismatch losses due to different cell temperatures. Cell temperature differences of up to 7°C (cell near the water inlet compared to a cell at the

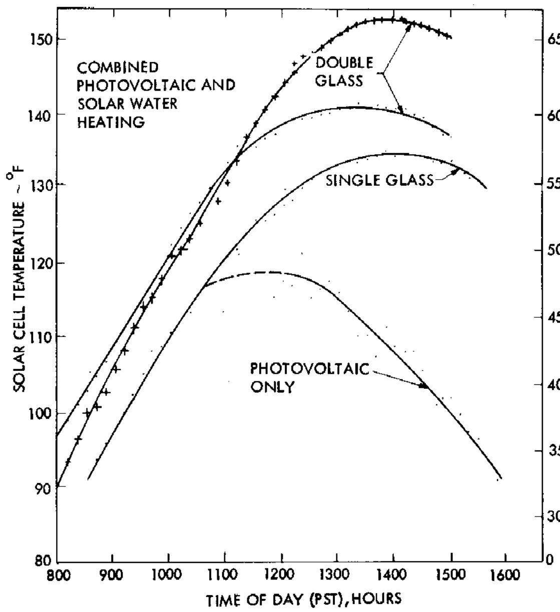


Fig. 11 Solar cell temperature vs time of day for photovoltaic-only and combined photovoltaic/thermal collectors.

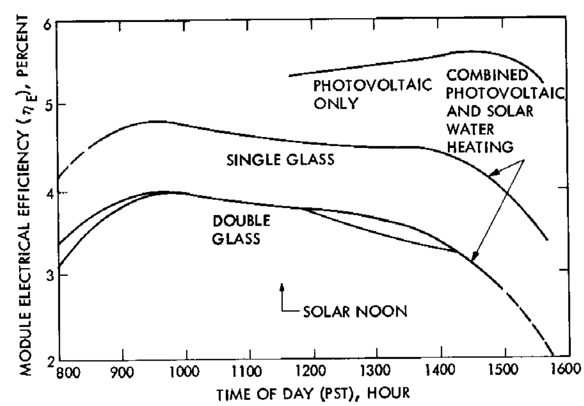


Fig. 12 Electrical efficiency vs time of day for photovoltaic-only and combined photovoltaic/thermal collectors.

water outlet) can be expected at the lower flow rate. The highest test flow rate cut this difference in half. In an actual system, the pump requirements will dictate the more common lower flow rate and an additional 1-2% decrease in photovoltaic power is probable.

Three tests were carried out. In the first test a single glass was used, and the water temperature increased linearly up to 54°C (130°F) by 1400 (2:00 p.m.) PST. The second test was carried out using a double glass configuration, and the results showed approximately the same water temperature profile. In the third test, also with the double glass, an electrical heater was turned on at 10:45 PST to simulate a slightly higher temperature system. The final water temperature reached was 64.4°C (148°F). Figure 11 presents cell temperature as a function of time for these three tests plus the cell temperature for the same photovoltaic module in a normal field installation with air cooling only. Cell temperatures for the first half of the morning for the combined configuration are similar to, and on occasion may be lower than, the air-cooled-only configuration depending on the initial temperature of the storage water. By mid or late morning, however, the cell temperature for the combined configuration exceeds that of the air-cooled-only configuration, and it remains significantly warmer throughout the afternoon, during which period the temperature of the air-cooled module actually decreases.

Since power for the photovoltaic-only module decreases at a rate 0.4%/°C increase in cell temperature, the higher module temperatures, especially in the afternoon, contribute significantly to lessening the electrical performance. Figure 12 presents the electrical efficiency (η_e) as a function of time for the same tests and cell temperatures corresponding to those presented in Fig. 11.

Table 4 is a summary of electrical efficiency η_e for an 8-h operating period, including the solar noon measurements. To obtain the 8-h average, it was necessary to extrapolate the curves in Fig. 12. The η_e of the photovoltaic module alone was assumed to be the same in the morning as measured in the afternoon. Analysis indicates that this is approximately true, but generally the efficiency will be slightly higher in the morning because of cooler air temperatures. The effect of a single glass, of double glass, and of the higher afternoon water temperatures on η_e are illustrated in Table 4. It is also apparent that η_e for the noon hour is less than the daily average for the photovoltaic module alone, but greater than the 8-h daily average for the combined configurations. Compared to the daily average, the noon average performance predicts a higher performance by 2, 7, and 9%, for the single and two double glass configurations, respectively, and a 2% lower performance for the photovoltaic only module.

The purpose of the last two tests was to estimate the change in η_e which occurred with a change in water storage temperature. The comparison was less than ideal because of the difference in the initial water storage temperatures. However, assuming morning values for η_e to be the same, and basing the estimated change in η_e only on the change in afternoon performance, the estimated values for electrical efficiency are minimum but representative of actual values. The minimum change in daily electrical performance for a change in water storage temperature is thus estimated at 0.014%/°C for the double glass configuration. Figure 13 graphically illustrates this effect. Approximately a 50% reduction in η_e from that for the photovoltaic module alone would be approached with a combined module and 100°C fluid storage, as occurs for Solar House I.

Table 4 Electrical efficiency (η_e) of photovoltaic only and combined photovoltaic/thermal collectors

		Combined modules		
			Double glass water storage	
Time period	Photovoltaic only	Single Glass	55.6°C	64.4°C
Morning	5.49	4.64	3.72	3.85
Afternoon	5.49	4.32	3.34	3.10
Daily	5.49	4.48	3.53	3.48
Noon	5.37	4.58	3.78	3.78

Table 5 Preliminary economic implications of combined collectors

		1982 cost, $/W			1986 cost, $/W		
Collector configuration	Water exit temp., °C	Cells	Sub	Total	Cells	Sub	Total
PV only	-	1.80	0.20	2.00	0.34	0.16	0.50
Combined (single glass)	60	2.21	0	2.21	0.40	0	0.40
Combined (double glass)	60	2.45	0	2.45	0.46	0	0.46
	100	2.70	0	2.70	0.51	0	0.51

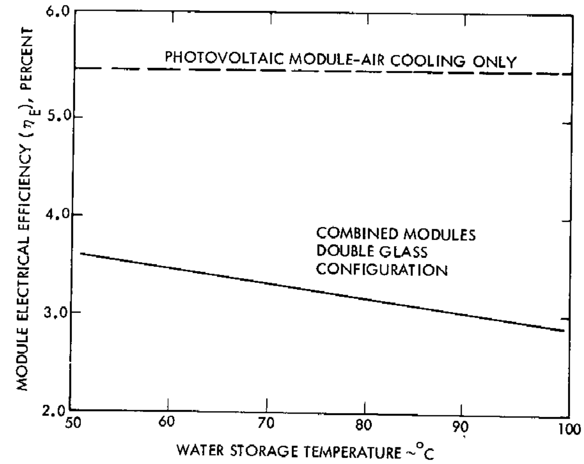


Fig. 13 Effect of water storage temperature on the electrical efficiency of a combined photovoltaic/thermal collector.

Since the danger of a decrease in flow rate is of concern with this type of combined module, a test was made to illustrate this effect. Additional heat was added to the storage water and the cell temperature was elevated to 75.6°C by 11:00 PST, at which time the flow was stopped. The cell temperature continued to increase to a maximum of 91.1°C at 12:30 PST. This temperature is not cause for concern; however, such a failure on a hot day and with a thermally more efficient system would result in cell temperatures greater than 100°C and perhaps as high as 130°C. New material problems may begin to show up at the latter temperature.

Table 5 is an estimated cost summary in $/W formulated from the preceding efficiencies and 1980 and 1986 photovoltaic module cost goals. The optimistic estimates assume that all noncell-related costs are absorbed by the solar water heating module. Sometime in the 1980-1984 time period, the marriage configurations may be cost effective in remote applications. Beginning in 1986, the combined module for moderate storage temperatures could reduce the cost to less than $.50/W. For residential applications, the combined module will be most desirable.

Phase Change Cooling

There have been several applications, both terrestrial and in space, in which the latent heat of fusion is used to absorb excess energy to limit an otherwise unacceptable rise in temperature. A variety of phase change materials are available so that correspondence between the desired melting point and application are easily obtainable if cost is not a primary consideration. Cost is a primary factor for the LSA project, and only a few of the waxes have the potential to be a cost-effective means of lowering or limiting the photovoltaic module temperature.

Examination of the properties of three waxes[6] whose projected costs/lb for large commercial quantities show potential for thermal storage applications reveals that Eicosane has a melting point (36.7°C) 4°C to 7°C less than the NOCT of the block II modules (41°C to 47°C). Therefore, if the phase change material was successful in absorbing the excess thermal energy, an improvement in power of 2-3.5% could be expected.

A Spectrolab block I module was enclosed on the back side as illustrated in Fig. 14. The module aluminum substrate was in direct contact with the wax. The test configuration was that normally used for the NOCT measurement with the module mounted in an array and surrounded either by other modules or by black plates simulating other modules. The tilt angle of the array was adjusted to maintain the module normal to the sun at solar noon. Technical grade Eicosane and common canning paraffin were used for the phase change materials.

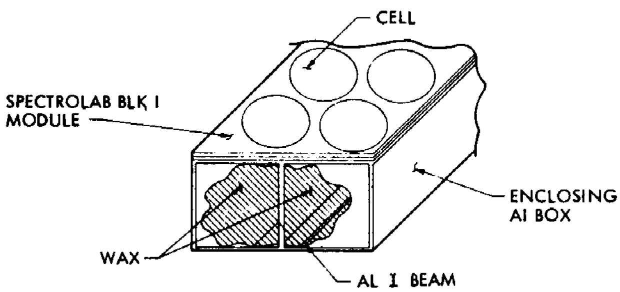


Fig. 14 Phase change photovoltaic module.

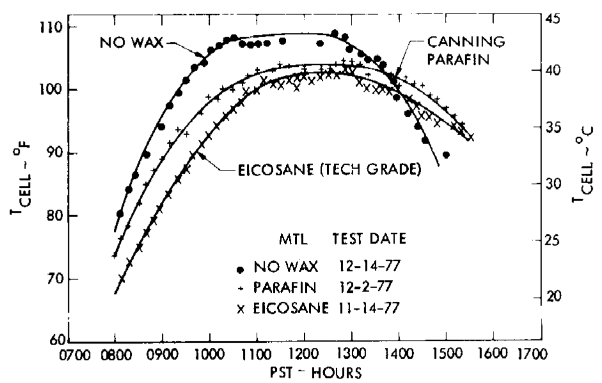


Fig. 15 Cell temperature during tests with phase change materials.

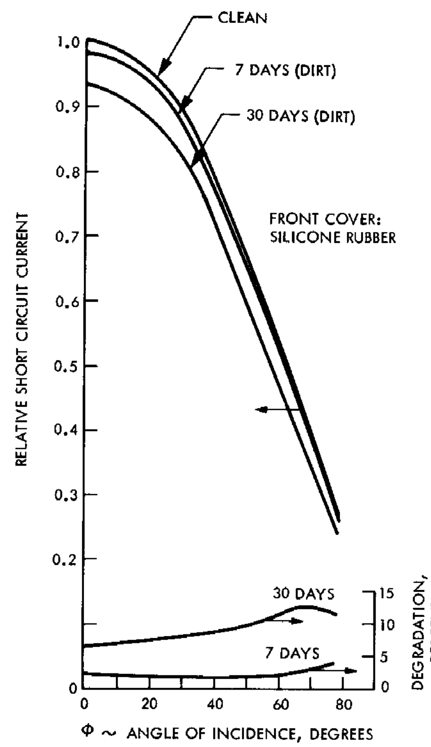


Fig. 16 Short-circuit current vs angle of incidence and dirt buildup.

The canning paraffin was purchased at a local supermarket for $.43/lb and the technical grade Eicosane costs $1.70/lb.

The electrical efficiency (η_ϵ) is based on the photovoltaic module area and is as defined previously. Table 6 summarizes η_ϵ for the three tests. Performance is based on 8 h of operation. The Spectrolab module has a very low NOCT (41°C) that was made lower by the attachment of the aluminum box. Therefore, the small improvement of 1.2% (paraffin) and 1.4% (Eicosane) was about as expected. The improvements are minimal since the air temperature as well as the solar intensity was the same or greater on the days during which the wax was used; higher cell temperatures would have resulted without use of wax on those days. Figure 15 shows the cell temperature for each test, and the effect of the wax is more evident. During the test only a portion of the Eicosane melted and no melting occurred with the paraffin because of its high melting point. The heated wax keeps the cell temperature higher during the last two hours of the day. Because of radiation to the night sky, the module and wax cool to less than the night air temperature, which increases the thermal storage capacity and accounts for the initial lower cell temperatures.

The tests have illustrated that better photovoltaic performance can be obtained with a phase change material. However, current prices of the waxes make the technique too expensive. Even with predicted future price reductions (assuming increased production), using a phase change material would probably only be cost-effective in some of the remotest applications.

Table 6 Electrical efficiency (η_ϵ) results

Phase change material	η_ϵ, %	Improvement, %
None	5.73	0.0
Canning paraffin	5.80	1.22
Tech grade Eicosane	5.81	1.40

Electrical Performance of Dirty Modules

The module short-circuit current was measured in natural sunlight at solar noon for several angles of incidence obtained by changing the tilt angles of the module. When the module is clean, measurements indicate the short-circuit current varies as the cosine of the incident angle for either a front surface of glass or Sylgard 184. Figure 16 illustrates the effect of dirt accumulation for a Sylgard 184 module. After one week of dirt accumulation, the degradation is about 2% and constant for angles of incidence up to 60 deg. After one month, the degradation is 6.5% at normal incidence and increases almost linearly to 11.5% at an angle of incidence of 60 deg.

These tests show that normal incidence measurements of the effect of dirt are only representative of "light" dirt accumulation as might be expected for modules washed at two-week intervals. In a "severe" dirt environment, the degradation is greater than that indicated by the normal measurements.

Conclusions

Photovoltaic Module Thermal Performance

Figure 17 summarizes the NOCT measurements of the modules and illustrates the trend in NOCT. Care in thermal design and cost considerations are forcing the NOCT into the 45-48°C range. Good thermal design utilizes a thin substrate with high infrared emission and low solar absorption, and the module has no air voids. Very little additonal thermal improvement is possible with the flat-plate configuration. This is apparent on examining the NOCT efficiency (η_{NOCT}) and the two parameters whose product results in NOCT. As shown in Table 7, η_{NOCT} is between 0.90 and 0.93 for the block II modules. If the lowest maximum power coefficient (Table 7) is combined with the minimum temperature difference (NOCT-28°C), then η_{NOCT} is equal to 0.94. Because of cost, 0.94 probably represents a practical upper limit of η_{NOCT} obtainable for the flat-plate configuration. Good thermal design, as typified by the block II modules, results in thermal performance within 1 and 4% of that probably obtainable from the thermally optimum realistic design.

Table 7 NOCT and η_{NOCT} summary

Block II module	NOCT, °C	Max. power coeff.	×	NOCT − 28°C	=	η_{NOCT}	No. of tests performed
Sensor tech	43.0	0.00505		15.0		0.924	6
Spectrolab	41.1	0.00524		13.1		0.931	9
Solarex	47.0	0.00451		19.0		0.914	6
Solar power	46.0	0.00546		18.0		0.902	2

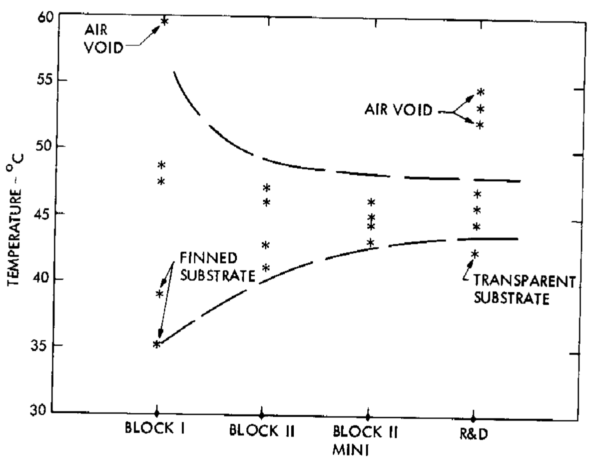


Fig. 17 NOCT summary.

Water-Cooled Module

Significant improvement in module performance is possible by cooling the module with water. However, cooling with water is not expected to be cost-effective unless the application already involves pumping of the water (irrigation, swimming pools, etc.), or unless a gravity water-feed system is possible.

Combined Photovoltaic and Solar Water Heating Module

Tests and cost estimates indicate that a combined photovoltaic and solar water heating module might be cost-effective in the mid 1980s. Sandia is currently evaluating several combined thermal/photovoltaic collectors. Both water and air heating modules are included in this study.

Combined Photovoltaic and Thermal Storage System

Reducing the module temperature by using a phase change material is not cost-effective. If thermal energy stored in the phase change material is also utilized, a combined photovoltaic and thermal storage system may prove to be cost-effective. One concept employs the lightweight solar dome developed by Boeing, with paraffin wax as the phase change material for thermal storage. Since the wax is total contained, the building return air can, on command, be diverted to and heated directly in the combined photovoltaic and thermal storage area. Water at city line pressure is also routed through the wax for preheating prior to entering the normal water heater.

At the wax melting point, more energy can be stored with about 15% less weight than with water. Therefore, this type of system will be better suited for roof (apartment and industrial buildings) and residential attic installations. For residential installation the dome would be replaced by glass, and double glass may be desirable to minimize nighttime losses. Optimization of this concept will vary with the application. However, eliminating the secondary loop by placing the thermal storage system in the primary water and space heating loops and thus utilizing the existing space heating fan, city water pressure and existing attic or roof space will result in lighter weight and in cost savings which make the concept deserving of additional study.

Electrical Performance of Dirty Modules

Tests of the effect of dirt indicate that "normal incidence" measurements are actually representative of "light" dirt accumulation. In a "severe" dirt environment, the degradation is greater than that indicated by the normal measurements. As reported in the LSA Quarterly Report of April-June, 1977, a 6.5% degradation based on normal incidence for angles of incidence up to 60 deg, increases to 8% when weighted according to the annual energy output as a function of incidence angle.

Acknowledgment

The work in this paper was carried out at the Jet Propulsion Laboratory, California Insitute of Technology, under the sponsorship of the Department of Energy by agreement with the National Aeronautics and Space Administration.

References

[1] Stultz, J. W. and Wen, L. C., "Thermal Performance Testing and Analysis of Photovoltaic Modules in Natural Sunlight," LSA Task Report 5101-31 (JPL internal document), July 29, 1977.

[2] Stultz, J. W., "Thermal and Other Tests of Photovoltaic Modules Performed in Natural Sunlight," LSA Task Report 5101-76 (JPL internal document), July 31, 1978.

[3] Namkoong, D., "Nominal Operating Cell Temperature (NOCT) Test," NASA/Lewis Research Center Document 4220-027, Dec. 5, 1977.

[4] Dans, E. S. and Wen, L. C., "Solar Heating and Cooling Systems for Building: Technology and Selected Case Studies," LSA Task Report 5040-9, Rev. 1 (JPL internal document), Nov. 1975.

[5] Loef, G. O. G. and Ward, D. S., "United States Special Format Report: Design, Construction, and testing of the Colorado State University Solar House 1 Heating and Cooling System," ERDA C00-2577-76/1, June 1976.

[6] Shelpuk, B., Joy, R., and Cronthamel, M., "Technical and Economic Feasibility of Thermal Storage," RCA Advanced Technology Laboratories, Document C00/2591-76/1, June, 1976.